COVER SHEET

Distributed Generation Diversity Level for Optimal Investment Planning

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ABSTRACT

The task of improving the supply quality and maintaining supply continuity during emergencies has become more feasible for a distribution company (DISCO), owing to new developments in Distributed Generation (DG) technologies. Even though the technical issues regarding DG interconnection to the main grid are of great importance and are being addressed by on-going research, it must be clearly placed in the context of on the financial performance of the utility. In this paper, a general approach to quantify the technical benefits of DG employment is proposed. The power system economic impact is assessed by evaluating supply quality, supply reliability, system power losses and capital investment. Moreover, the rationale for this research also includes the possibility of DG diversity level in contribution to the economical benefits from DG integration. The approach is tested by a system which is developed from a Tasmanian distribution example. Simulation results and discussion are presented to illustrate the effectiveness and usefulness of the method.

Index Terms—*Distributed Generation, Distribution System Planning, Supply Quality, Supply Reliability, Power Loss, Cost Analysis.*

1. INTRODUCTION

The world-wide electric power system is experiencing dramatic changes in the system configuration due to numerous technical and economic factors. Formerly, it was more beneficial for the utilities to transfer energy from a few large central generations through the transmission and distribution systems to the customers [1]. Nevertheless, in the near future, the power system will tend to be more decentralised, with increasing numbers of smaller generating units connected directly to the distribution or customer levels, close to the consumption centre [2]. This new trend is expected to address the needs of distribution companies (DISCOs) to meet the rapid load growth, to provide the customers with a higher quality and more reliability supply, and to achieve more flexible electric systems, energy savings, minimisation environmental impacts and improve their return on investment with less investment risk [3-6]. These small generators are known as Distributed Generation (DG).

The major differences in characteristics between conventional central generation and DG are their sizes and locations [7]. While central generations have large capacity and connected to the high voltage transmission lines, DGs are much smaller, depending on the applied technologies, and integrated to the main grid at medium and low voltage levels. DGs are defined into many categories based on the energy resources, capacity limit, the amount gas emissions, etc. [8]. The most common types of DG utilise conventional fossil fuel such as gas, diesel and coal to produce electricity. Recently, the diminished supplies and cost of the conventional fossil fuel has sparked a new interest and initiated further research and development in fuel cell technology and renewable energy resources. Popular renewable energy technologies include wind turbine, photovoltaics, biomass system, geothermal, etc. [9]. The attraction of the DG solution has come from the many benefits it brings to both the utilities and customers. Several significant benefits, which are already validated by practice, consist of improving voltage profile, reducing power losses, enhancing the security and reliability of power supply, reducing emissions, and deferring further upgrades on transmission and distribution systems [10-12].

Different studies have been proposed in the literature to assess the potential economic benefits obtained from DG. The results from these studies made it easier for the planning engineers to design the distribution system with DG connection in the most cost-effective way. In [13], a comprehensive analysis of the economic benefits accrued to the DISCO investing in DG has been presented. The main objectives of the model are to minimise the capital investment, operating costs and payment toward loss compensation. Authors in [14] have come up with a general approach to assess and quantify some technical benefits of DG in terms of voltage improvement, line-loss reduction, and environmental impact reduction. One paper [4] has presented a new integrated model for solving the distribution system planning toward minimising DG investment, system losses, as well as cost of DG power and power purchased from the main grid. Another methodology has been developed in [15] to evaluate the financial impact of DG on distribution networks and businesses. In [16], an algorithm based on the Tabu search has been proposed to find optimum locations and sizes of DG for minimum cost of energy loss.

In this paper, we present a cost analysis to evaluate the long term economic benefits obtained by DG with current loading patterns. The output of this methodology quantifies the financial performance of a distribution system in term of supply quality and reliability cost, power loss cost and capital investment. Comparison between the performance of system with and without DG(s) will provide an evaluation of the contribution of DG(s) to minimising the overall expenses of the utilities.

2. PROBLEM FORMULATION

The aim of this research is to develop a criterion which is able to provide fundamental support to the distribution planning engineers regarding the DG employment decision-making. DG is defined to be feasible for integration into distribution system only if it provides a better service to the customers and reduces the overall costs to the community. The problem deals with multiple objectives and therefore a compromise should be made in order to satisfy both utility and customers. This section presents a brief discussion on the DG benefits to the end-users and to the utilities. Then a performance index is introduced which can be comprehensively used to assess and quantify the general economic impact of DG.

2.1. BENEFITS OF DG TO THE UTILITIES

DG has become attractive to the utilities due to its capability to reduce the costs and thus increase the overall profits with:

1. Reducing the payment towards the supply quality and outages.
2. Reducing the payment towards grid power losses.
3. Reducing the delivery cost by serving loads locally.
4. Reducing the reserve margins and increasing the energy efficiency, therefore, reducing the capital and operation costs in some cases.
5. Reducing or deferring the upgrading costs for transmission and distribution facilities.

2.2. BENEFITS OF DG TO THE CUSTOMERS

It has been proven by literature that DG benefits customers in numerous ways, including both technical and economic:

1. Provides customers with an alternative electricity sources.
2. Utilises heat, waste, or by-products from other process if available to produce electricity.
3. Reduces the electricity bills, especially in case of small and remote customers.
4. Improve the supply quality, security and reliability.
5. Reduces the amount of emissions.

2.3. PERFORMANCE INDEX

Realistically, the decision for system planning is reached through economic verification. For this reason, the capital investment on DG, which is usually high, requires to be carefully assessed and verified once implementation. In this paper, the financial viability of DG system is determined by a single index, called performance index (PI). This index is able to evaluate major DG benefits, which are believed to mainly contribute to the utility's profit or community benefit, against the overall cost for DG installation. In order to examine long-term effect of DG investment, the PI is expressed as the net present value (in term of dollars) of total system operational expenditures in *t* years. This equals to the summation of the present values of four primary individual items, which are shown in Fig.1. The present value is actually the equivalent of future worth for the whole planning period at the present time [17].

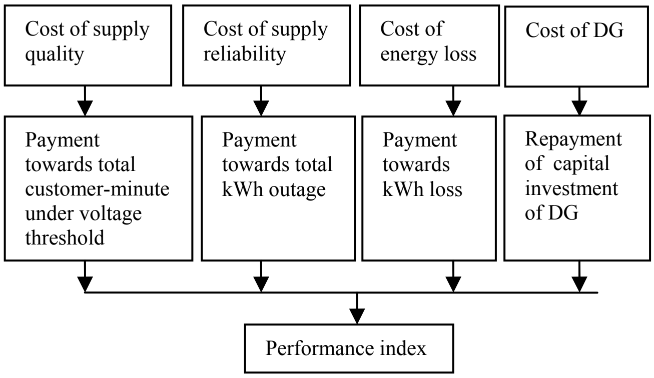

Figure 1: Elements affect the system financial performance

According to Fig.1, the smaller the PI, the better the overall performance of distribution system on the cost figure.

3. APPROACH

The evaluation methodology of each cost involved in the decision-making process, including supply quality, supply reliability, power loss and DG, is presented in this section. From this, the value of the PI can be calculated.

3.1. COST OF SUPPLY QUALITY

One of the well-known justifications for DG employment is that DG has ability to improve the voltage profile of the system. It is a common problem that customers in the remote areas suffer from low voltage condition. This may cause malfunction or in some situations, destruction of the connected electrical appliances. The real and reactive power injection from the DG partly reduces the load burden on the distribution lines, and thus increases the system voltage by an amount of ΔV, given in Eq.(1) [18],

$$\Delta V = \frac{RP_{DG} + XQ_{DG}}{V} \tag{1}$$

where R and X are the equivalent line resistance and reactance, respectively. P_{DG} and Q_{DG} are the DG generating real and reactive power, respectively. V and ΔV is the voltage and voltage variation, respectively.

The supply quality is evaluated by System Average Under-specification Duration Index (SAUDI). The index defines the average duration when the supplied voltage is below specification for customers served during a specified time period. SAUDI is calculated by taking the summation of customer-minutes under voltage problem during that examined period of time and dividing the sum by the average number of customers served during that period, as given in Eq.(2),

$$\text{SAUDI} = \frac{\sum_{i=1}^{TU} N_i^U \times t_i^U}{SN} \tag{2}$$

where N_i^U is under-threshold customer i, t_i^U is the under-threshold duration of customer i throughout the examined period, NU is the total number of under-threshold customers, and SN is the total number of customers served.

To convert SAUDI into cost function, it is multiplied by the total number of customer connected to the system and the rate of payment toward one customer-minute under voltage threshold. Therefore, the cost of supply quality can be computed by Eq.(3),

$$\text{Cost of Supply Quality} = \text{SAUDI} \times \text{SN} \times \text{rate}_{\text{SQ}} \tag{3}$$

where unit of rate_{SQ} is dollars per customer-minute below specification.

3.2. COST OF SUPPLY RELIABILITY

Supply reliability is another great concern of the utility due to its enormous cost implications for end-users. This issue is particularly important in case that the system is connected to large industrial customers or critical loads such as hospitals, where even short time outage can not be tolerated and may result in high cost penalties paid by DISCO [17]. DG is one of the effective solutions to improve the system reliability. It provides back-up service during permanent failures, restoration or maintenance operations, and thus increases the reserve margin of the power system. Also, it may play role as an alternative source or addition to the total system generating capacity.

The supply reliability is evaluated by System Average Interruption Duration Index (SAIDI). The index defines the average interrupted duration for customers served during a specified time period [19]. SAIDI is calculated by taking the summation of customer-minutes outage under interruption events during that examined period of time and dividing the sum by the average number of customers served during that period, as given in Eq.(4),

$$\text{SAIDI} = \frac{\sum_{i=1}^{E}\sum_{j=1}^{TI} N_{ij}^I \times t_{ij}^I}{SN} \tag{4}$$

where N_{ij}^I is interrupted customer j during interruption event i, t_{ij}^I is the interrupted duration of customer j during interruption event i, TI is total number of interrupted customers during interruption event i, and E is total number of interruption events throughout the examined period.

The dollar penalties regarding to loss of supply is calculated by multiplying the SAIDI by the total number of customer connected to the system and the rate of payment for one customer minute outage, as in Eq.(5)

$$\text{Cost of Supply Reliability} = \text{SAIDI} \times \text{SN} \times \text{rate}_{\text{SR}} \tag{5}$$

where unit of rate_{SR} is dollars per customer-minute outage.

3.3. COST OF ENERGY LOSS

Energy losses are always an unwanted factor of power system operation. They lower the efficiency of electricity transfer and the situation is particularly serious during peak hours for long radial systems. To cover this loss, DISCO has to purchase extra power from generating company and this fee is usually passed on to customers. The loss is unavoidable, yet can be reduced by employing DG. As DG injects reverse current, the current flows on the distribution lines are reduced and the loss will decrease as a result. In this paper, only the cost associated with real power loss will be considered since reactive power loss is normally compensated by shunt capacitors. However, costs associated with reactive power loss can also be included if desired.

The cost of energy loss is calculated by Eq.(6),

$$\text{Cost of Energy Loss} = \Sigma \text{ kWh loss} \times \text{rate}_{\text{EL}} \tag{6}$$

where unit of rate_{EL} is dollars per kWh loss.

3.4. CAPITAL INVESTMENT OF DG

The cost of DG integration can be divided into three categories, which include equipment and installation cost, operation cost and maintenance cost. While the equipment and installation cost, as well as maintenance cost, are related to the size of DG employed, the operation cost is related to the DG running time.

There are a variety of DG capital investment levels depending on applied DG technology. Basically, DG technologies can be divided into several categories, which are reciprocating engines, turbines, fuel cells, and renewable [20]. Among these categories, reciprocating engines appear to have the lowest equipment and installation cost, turbines and fuel cells are the next cheap technologies, and the renewable DGs are the most expensive ones. Maintenance cost is associated to both the size and employed technology of DG, thus they can be reasonably determined in term of percentage of the equipment and installation cost. For long term planning consideration, another factor needs to be included which is the DG's lifetime. It is expected that further costs related to DG equipment and installation is required after every certain amount of time.

The cost-effective level of DG in a system thus can be determined by summing four major expenditures of the utilities. Long-term planning quantification with PI can be made by compounding the payment of each period with the annual interest rate. Elements of PI, which have been discussed in details above, have been selected in such a way that key potential contribution from DG will be fully investigated.

4. TEST SYSTEM

The modified distribution system under study is shown in Fig.2. This is a 48-km radial feeder connecting between Smithton substation and Woolnorth, which belongs to Tasmanian Distribution Company, known as Aurora Energy. The test feeder has line impedance of Z_l = 0.6672 + j0.3745 Ω/km. Nominal voltage at the substation V_S is 22 kV and Thevenin equivalent source impedance is 0.7278 + j2.6802 Ω. For reduced complexity, we assume that the total feeder load is uniformly distributed at 69 load buses along the main feeder.

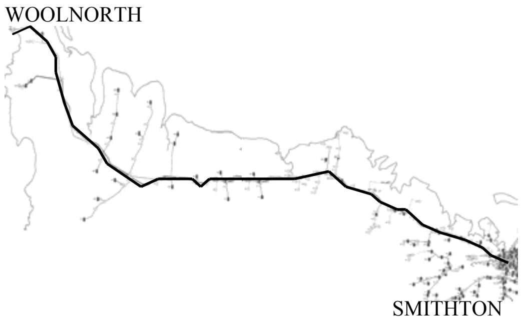

Figure 2: Smithton – Woolnorth test feeder

Even though it is possible to obtain accurate load data by installing measurement and data acquisition devices at the interested feeders throughout the year, the solution is too costly and time consuming. Alternatively, yearly load data can be reasonably created with basic knowledge of system load and load variation factors. Following is the procedure which was used to produce feeder load data for the test system (Fig.3).

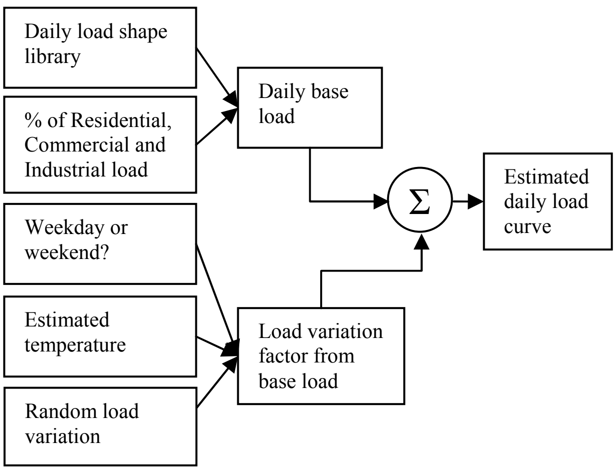

Figure 3: Daily load estimation procedure

Daily load data is adapted from [21] with the percentage of residential, commercial and industrial load are 70%, 20% and 10%, respectively. The total real and reactive power drawn from the load in a standard day is shown in Fig.4.

In this paper, we assume that 100% of loads are on from Monday to Thursday. However, only 90% and 70% of them are on-line on Friday and weekends (Saturday and Sunday), respectively. This is due to the reason that mostly industrial loads and partly residential and commercial loads are not connected to the grid during weekends. Random factors are also added to the base load to produce different load patterns for different days during the year. The daily load variation of the feeder is assumed to be within 5%. Weekly load curve from Monday to Sunday is shown in Fig.5, which indicates that heavy loaded conditions should be expected during the weekdays.

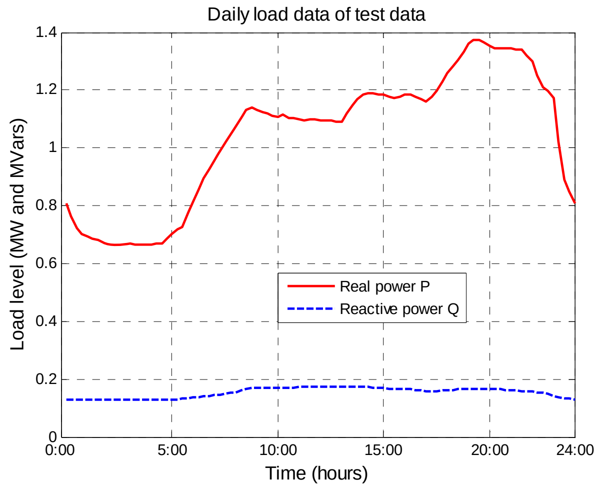

Figure 4: Standard daily load curve

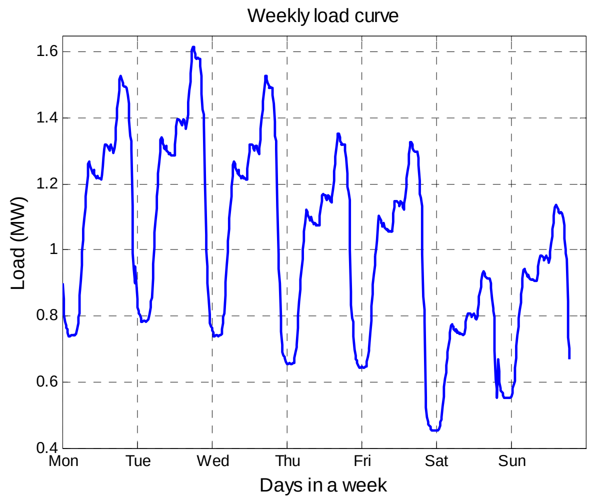

Figure 5: Standard weekly load curve

The load is also affected by seasonal feature for the changes in temperature. The next figure, Fig.6, shows the mean daily maximum and minimum temperatures in Celsius degrees from January to December in Hobart [22]. It can be seen from Fig.6 that the mean temperature changes accordingly to four seasons in a year. Minimum temperature occurs during peak winter time in July and maximum temperature happens in January or February. Again, random factors are used to create daily profile of temperature, of which full knowledge is lacking. The daily temperatures are assumed to vary with 2-3% around their mean value. Fig.7 shows the daily high and low temperature data in a year which is used for this test system.

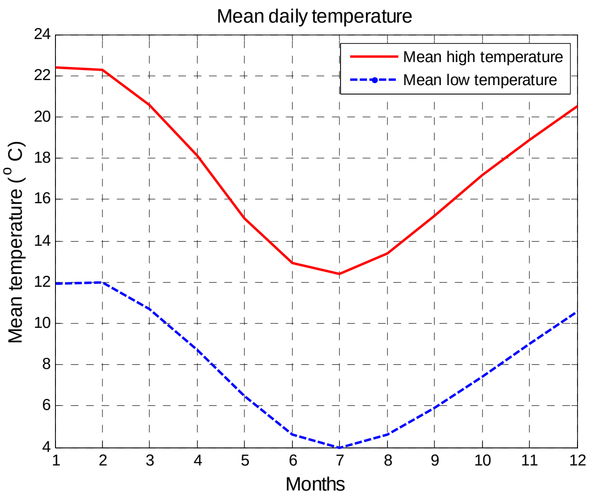

Figure 6: Mean daily high and low temperature in a year

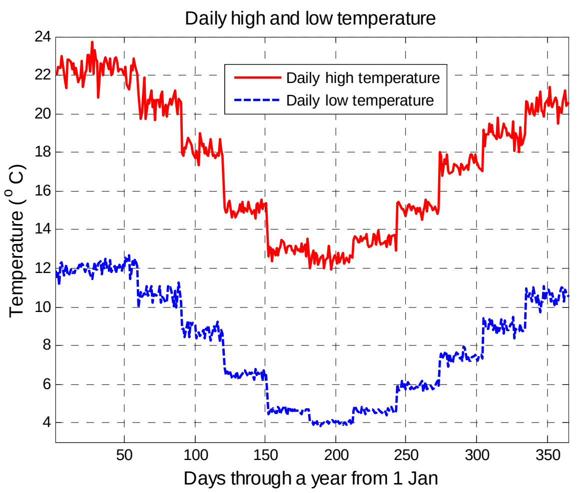

Figure 7: Daily high and low temperature in a year

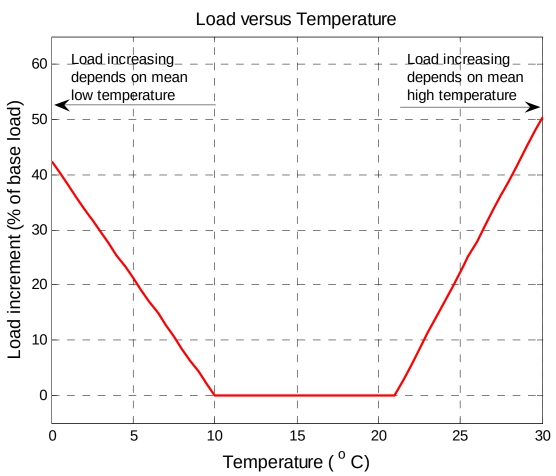

Figure 8: System load versus temperature

Temperature in a day alters the load level as people tend to use heaters in cold days and air conditioners or fans in hot days. Thus, more loads are connected to the main grid either when the temperature rises too high or drops too low. For this reason, we can assume that the increment of load during hot weather is defined based on daily high temperature, while during cold weather it is calculated according to daily low temperature. In reality, the relationship between load and temperature is non linear, however, it is linearised in this study for simplicity. The addition of load due to seasonal factor is computed in term of percentage of the base load. If the low temperature of the day is lower than 10 degrees, the load would start increasing with the rate of – 4.24 percents of base load/degree Celsius. However, in case that high temperature gets higher than 21, the increasing rate of load is then 5.585, as shown in Fig.8.

The daily peak load in a year is shown graphically in Fig.9, which illustrates the tendency of load change during the year. The system load is low during autumn and spring, higher in summer and reaches its peak value in winter time. Fig.9 also reveals the Tasmanian load characteristics with huge number of heating loads compared to cooling ones, the peak load in winter is considerably higher than that in summer. In the next figure, Fig.10, the yearly load duration curve is shown.

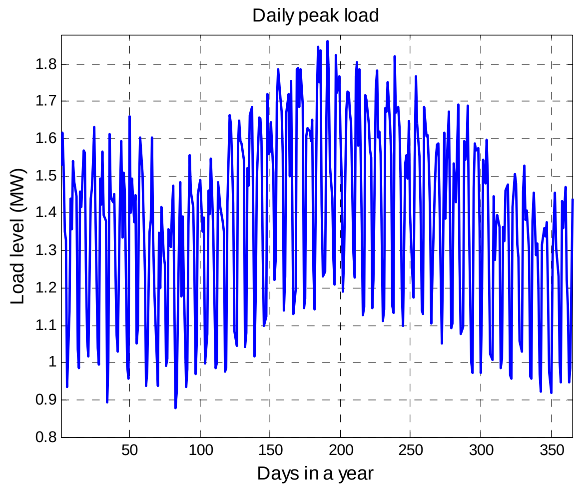

Figure 9: Daily peak load in a year

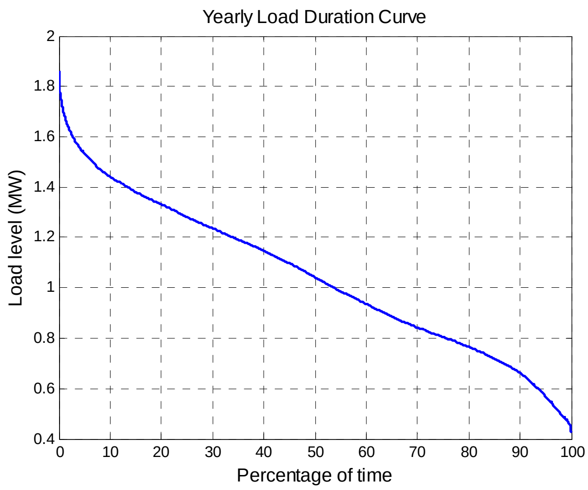

Figure 10: Yearly load duration curve

5. SIMULATION RESULTS AND DISCUSSIONS

In this section, the cost effectiveness and financial viability of DG investment are assessed. Different levels of DG diversity are considered in this study, such as no DG, single DG and multiple DGs. The performance index for each case is then computed and comparisons between different DG systems are made to determine the best DG planning decision.

5.1. TEST SCENARIOS

The financial benefits of DG are quantified by assessing the economic performance of test system over a term of 20 years. There are six DG planning scenarios to be explored in this part, including no DG, 1-DG, 2-DG, 3-DG, 4-DG, and 5-DG systems. To maintain the results' consistency, the same yearly load data, which has been mentioned in previous section, is used for all test scenarios. All measurements are performed every 15 minutes. During the time between one measurement to the next, the system parameters are assumed to be constant.

All DGs connected, work using an ON-OFF scheme, which is controlled by their local voltages. If the DG connection point voltage is larger than the higher reference voltage and present status of DG is ON, it will then be switched OFF. In the other hand, when the DG connection point voltage is smaller than the lower reference voltage and DG is currently OFF, it will be switched ON. DG sizes and DG locations in the test system are chosen as:

- For DG locations: If the system has one or more DGs, the first DG will be placed at the remote end and the others will be placed further from the remote end so that the distance between any 2 DGs is kept constant at 2.8 km. For example: in case the system has 4 DGs, they will be located at bus 69, 64, 59, and 54.
- For DG sizes: The highest penetration level is assigned for the DG at the remote end, then it is reduced by 50% for the next closest DG and so on. Total DG penetration in the system for all scenarios is 15% of the nominal peak load (1.6 MVA). For example: the system has 4 DGs at bus 69, 64, 59, and 54 will have the capacity of 8%, 4%, 2%, and 1% of the nominal peak load, respectively.
- The DG operating point, which is the ratio between real and reactive power injecting from DG, is set constantly at 1.78. This ratio ensures the maximum voltage improvement by DG [23].

5.2. ASSUMPTIONS AND COST DATA

The simulations are carried out with following assumptions:

a. The start-stop cost of DG is ignored.
b. The starting probability of DG is 90%. In other words, every time a DG unit is switched on, the probability that it fails to start is 10%.
c. Once a DG fails to start, the maintenance process will require DG off-line for the rest of the day.
d. Line fault probability is 1/km/year. Also, the ratio of permanent and transient fault is 1:5. The permanent fault requires 3 hours for repair, while transient fault can be automatically recovered with a successful reclosure. The probability of line fault is equal for any period of time and at any line section.
e. The protection devices of the test system include one automatic circuit breaker between bus 1 and bus 2, one automatic recloser between bus 34 and 35, and two manual air switches at two ends of each line section.
f. Operation times of circuit breaker, recloser and air switch are 2, 7, and 10 seconds, respectively. However, for air switches' manual operation, they also require travel time from the operator's place to the fault site. This travel velocity is 70 km/hr.
g. Once an island is formed, a control system is activated to control island's voltage and frequency.
h. All loads have automatic frequency load shedding mechanism.
i. DG life is 10 years.

Let us assume that the maximum demand of each customer after diversity is approximately 230 kW. The payment penalty toward each customer-minute under voltage specification is 1 dollar. The cost paid by utility for 1 MWh outage and 1 MWh loss are $10,000 and $25, respectively. The cost of DG equipment and installation (E&I) is 3000 dollars/$\sqrt{\text{kW}}$, which indicates that the larger size of DG installed, the smaller increasing rate of E&I cost. The initial investment of DG versus DG size is shown in Fig.11. The DG operating cost is of 30 cents/kWh, while the DG maintenance cost is 20% of the E&I cost. The interest rate is 7% per annum.

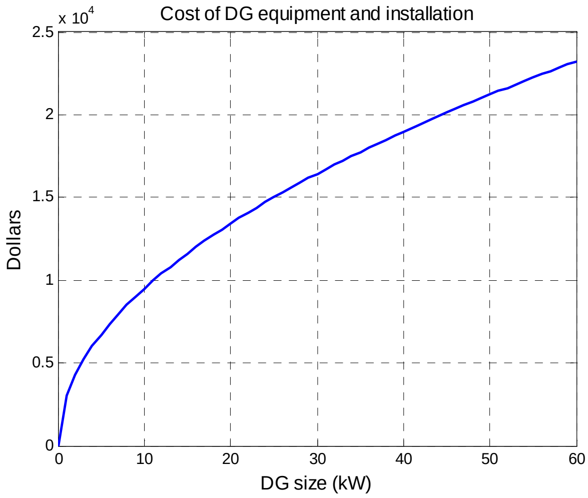

Figure 11: DG capital cost versus DG size

5.3. COST CALCULATIONS

Firstly, all the cost calculations for the one-year load cycle are performed with provided load data. After every 15 minutes, the load is measured and subjected to the analyses given in the next two figures to determine the total number of customer with voltage under specification, MW loss (Fig.12) and MW outage (Fig.13). The costs of supply quality and energy loss are then computed as proposed in sections III-A and III-C for the 15 minutes period.

In case of supply reliability cost, Fig.13 presents the simplified algorithm for MW outage determination with respect to one line fault at a specified line section on the feeder at an instant load level. The payment for customers not supplied in the 15 minutes is then computed by examining all possible line fault locations, taking the summation of all the cost paid toward each faulty case (provided in section III-B) multiplied by their probability, and finally, this summation is multiplied by the probability of line fault in 15 minute time. It should also be noted that for this study, the probability of each faulty case equals to 100% divided by the number of line sections. Next, the one-year cost data is calculated by summing all the values corresponding to 35041 intervals of measurement.

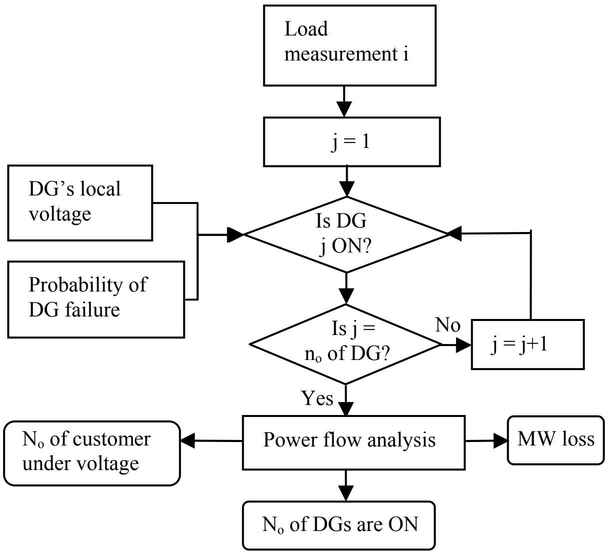

Figure 12: Analysis for supply quality and energy loss

Long term planning cost can be obtained by converting the payment of each year (or each 10 years in case of the equipment and installation cost of DG) compounded by the annual interest rate into the present value.

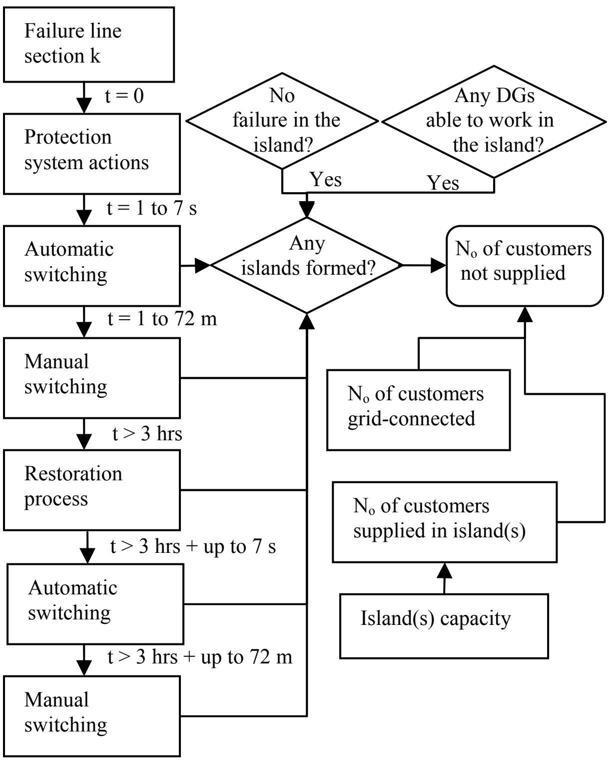

Figure 13: Analysis for supply reliability subjecting to line faults

5.4. SIMULATION RESULTS

In Fig.14, the effect of a single line fault, which is expressed in term of the customer minutes outage with respect to the load level, under different scenarios is shown. For this study, we consider up to N-2 scenarios only. In other words, there are maximum 2 failures, including line failure and DG failure, occur at any instant of time. The system used here has 5 DGs, which have the capacity of 7.35%, 3.67%, 1.84%, 1.22% and 0.92% penetration levels corresponding to DG 1 to DG 5, respectively. The figure shows the number of customer minutes lost is largest when DG 1 fails as DG 1 has the biggest capacity among all DGs in the system. This value decreases with the decreasing size of the faulty DG. The minimum value is obtained when all DGs are working. Also, the higher the load level, the higher number of customers who suffered from supply interruption.

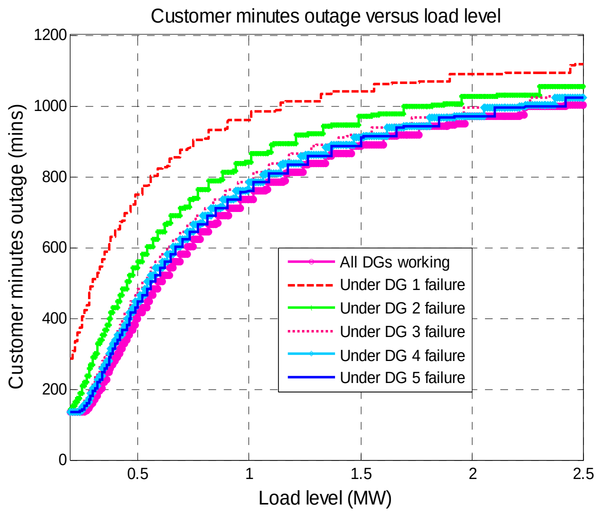

Figure 14: Interruption level versus load level under different failure scenarios

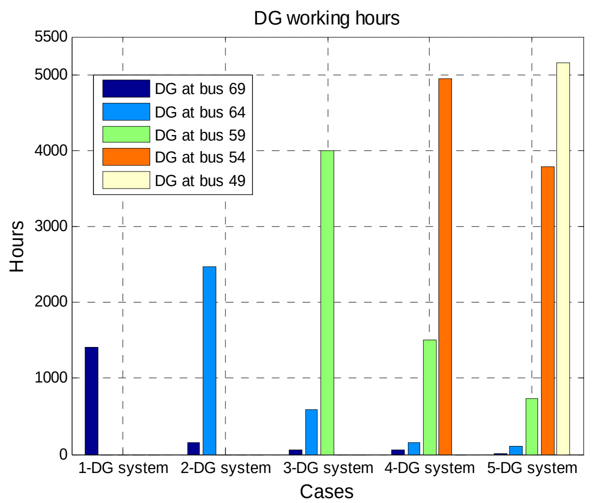

Figure 15: DG working hours in 20 years under different test cases

Next, the cost calculations are determined for all DG planning test cases mentioned above for comparison. Fig.15 illustrates the working duration of all DG(s) in 1 year according to six test cases. As in this particular study, DGs works on an ON-OFF scheme which is driven by the local voltage measurement; smaller DGs and located further from the remote end are likely to work more. As the number of DG increases, the burden of load is shared among DGs with the tendency of larger number of DG working hours for small DGs and smaller of that for big DGs. As the result, the DG operating cost decreases with more DG units installed in the system, as seen in Fig.16, since the running of big DGs are very costly. However, as the number of DGs reaches 5, the operation cost starts increasing. The equipment and installation, together with the maintenance costs, becomes larger as the number of DGs increase.

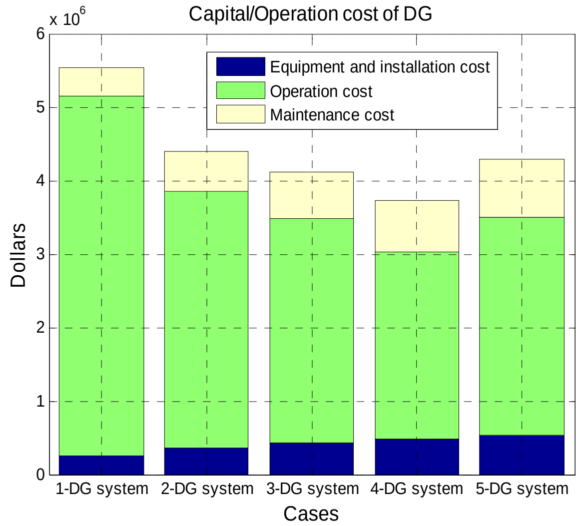

Figure 16: Total capital investment in 20 years as present value

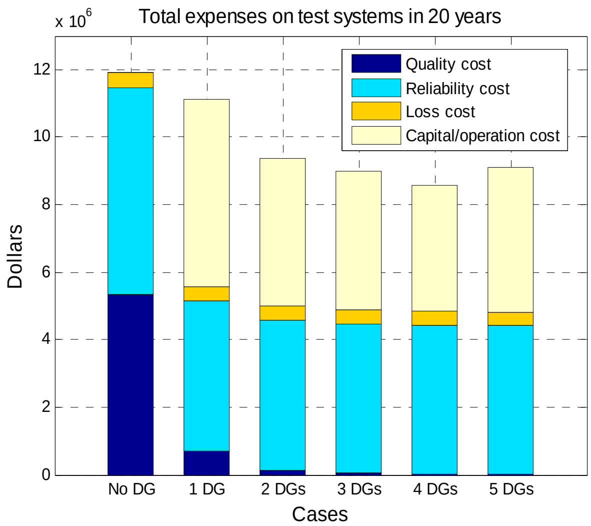

Figure 17: Cost figure in 20 years as present values for different test cases

In Fig.16, the payments toward each type of cost as well as the total cost of the six system planning scenarios, in 20 year term, are shown graphically. The cost values of supply quality, supply reliability and energy loss drop considerably in compare between the system with no DG and one DG. These costs keep reducing but with a smaller rate when the number of DG increases. Nevertheless, when there are more than 4 DGs present, the Capital/Operating cost for the DG system starts growing. The cost-effectiveness ranking of each test case, which is quantified by the performance index, illustrated in Fig.17, shows that the best planning option is to install 4 DGs in the feeder. Four DGs installed have improved the overall performance of the system with higher level of system quality and security and smaller level of line losses. Also, the capital investment for this system can be justified with a reasonable balance between the payment and the penalty reduction.

In this study, only a pure radial system without branching is considered. The result indicates that more than one DGs help us with improving the system quality, reliability and reduce losses. However, a lot of DGs is no more beneficial as the capital cost is too high. This work can be further expanded by developing the qualification method into a generic tool for DG planning optimisation in terms of DG size and location for branching systems. It is expected that the cost justification for more number of DGs installed will be achieved with branching systems. Furthermore, the test system uses a relatively high fault level with a high penalty on the supply reliability, which results in a high number of DG to reduce the total cost. On the other hand a system with a small value for the reliability penalty would require fewer DG's.

6. CONCLUSIONS

It is well known that DG can be incorporated into the distribution system as an alternative option to meet the load growth and provide the customers with a better electricity supply performance. However, the planning process for DG installation is of great important and needs to be done in the way that the overall community benefit from DG can be achieved maximised. In this paper, we have proposed a new methodology to quantify the cost effectiveness and financial attraction of DG system to the utilities using long term planning. The methodology has taken into consideration all the major potential benefits that can be contributed by DG, including supply quality improvement, supply reliability improvement and energy loss reduction. Also, a variety of major payments from DISCO toward DG investment has been covered. The methodology is applied and tested by a distribution system with one year load data. The simulation results show that the diversity level of DG has an enormous impact on the economic figure of the system, thus, careful assessment is required.

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